

SEARCH FOR A POSSIBLE SPONTANEOUS EMISSION OF MUONS FROM HEAVY NUCLEI

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A search for an exotic natural radioactivity of lead nuclei, using nuclear emulsion sheets as detector, is described. We discuss the experimental set-up of a test performed at the Gran Sasso National Laboratory (Italy), the event simulation, data analysis and preliminary results.

Keywords: nuclear decays; exotic radioactivity.

1. Introduction

In the late 80's, some theoretical work was dedicated to investigate possible exotic types of nuclear radioactivity, consisting in the emission of light particles such as pions or muons from heavy nuclei.^{1,2}

Muons or pions could be emitted by nuclei through the decays:²

$$(A, Z) \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu) + (A_1, Z_1) + \dots + (A_n, Z_n) \quad (1)$$

$$(A, Z) \rightarrow \pi^\pm(\pi^0) + (A_1, Z_1) + \dots + (A_n, Z_n) \quad (2)$$

where, for reasons of energy and momentum conservation, the number of fragments n is ≥ 2 . The nuclei (A_1, Z_1) , (A_2, Z_2) , ..., (A_n, Z_n) would yield a sequence of β^- decays leading finally to stable nuclei with a balanced neutron-proton ratio.

In ref. 2 some nuclear charge thresholds for different possible spontaneous particle emission were listed:

- (i) μ^\pm (prompt muon) for $Z \geq 72$
- (ii) π^\pm (prompt pion \rightarrow delayed muon) for $Z \geq 76$
- (iii) $2\mu^\pm$ (prompt muon pairs) for $Z \geq 91$

(iv) $2\pi^\pm$ (prompt pion pairs \rightarrow delayed muon pairs) for $Z \geq 100$

Natural lead is mainly composed by three nuclides: ^{206}Pb (24.1%), ^{207}Pb (22.1%) and ^{208}Pb (52.4%). They are stable nuclides, but the channels (i) and (ii) are energetically allowed.

In the hypothesis of the decays (1) and (2), the fission fragments would remain nearly at rest; most of the available energy would be used to produce the μ (or π) and the kinetic energies of μ and ν_μ (or π). The total kinetic energy Q_μ in a decay in 2 fragments with close values of A_1 and A_2 (symmetric fission) is ~ 30 MeV for negative muons and ~ 20 MeV for positive muons. Considering that the associated muon neutrino takes away a sizable fraction of this energy, the spectrum of emitted muons could be like in a β decay, with an average energy of $10 \div 15$ MeV.

The spontaneous or neutron induced fission of Pb has never been observed. A search for a Pb muonic decay can be made as a byproduct of the OPERA experiment,³ aimed to confirm neutrino oscillations in the parameter region indicated by some atmospheric neutrino experiments⁴⁻⁶. In the following, we discuss the experimental set-up, a Monte Carlo (MC) simulation and the reachable limits.

2. Experimental set-up

We propose to perform an experimental search for muonic radioactivity from lead nuclei in the low background conditions offered by the Gran Sasso underground Laboratory (LNGS). The low cosmic muon flux and the low natural radioactivity of the rock in the experimental halls of the LNGS provide unique conditions, allowing a potential discovery, or, at least, to establish a good upper limit for this exotic decay process. A detailed description of the different background sources is given in ref. 7.

The OPERA base element ("brick") is composed of 56 lead sheets (1 mm thick) interleaved with 2 nuclear emulsion sheets (43 μm thick) on both sides of a 200 μm thick plastic base. The area of each sheet is 10.3×12.8 cm^2 . The OPERA bricks (each containing a mass of 8.23 kg of Pb) could allow an experimental search for muon emission from lead, with exposures of several months. Their analyses with the fast automated optical microscopes⁸ would establish the local background contributions and validate the analysis procedures.

As the background rejection/reduction (see ref. 7) is a crucial point for this search, the detectors are surrounded on all sides by a shield, making a closed box structure. The shield is composed of an inner layer 5 cm thick of very pure copper followed by 15 cm of very low activity lead. The third layer

of the shield is a 3 cm thick polyethylene, in order to absorb neutrons^a. The set-up is located in the emulsion storage room, in hall B of the Gran Sasso Laboratory. The radon reduction is obtained with a ventilation system with fresh air forced circulation.

3. Monte Carlo simulation

A MC simulation program was implemented to estimate the occurrence of different event topologies. The simulation is based on the GEANT⁹ package applied to the OPERA lead/emulsion set-up. The simulation reproduces one complete OPERA brick, where muons of different energies (see the first column of Table 1) originate in random positions in the lead sheets. The initial muon directions are isotropically generated. We assumed different definitions for a candidate event, requiring that the muon crosses at least: (i) 2 emulsion films, (ii) 4 emulsion film (and thus also a lead plate) and (iii) 6 emulsion films (and thus also 2 lead plates). We also requested the detection of the decay positron or electron in at least (iv) 2, (v) 4 or (vi) 6 emulsion layers, together with the muon detection.

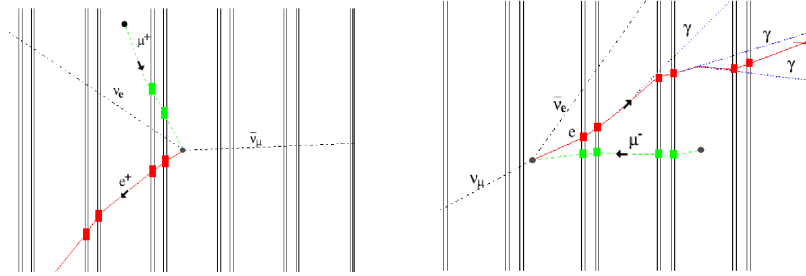


Fig. 1. Simulated events of spontaneous μ^+ (left) and μ^- (right) emission from lead inside an OPERA brick, assuming an initial muon kinetic energy of 15 MeV.

For each topology, the values quoted in Table 1 were obtained as averages over all possible muon emission directions. These estimates may be considered as geometrical efficiencies ϵ_g . The percentages of events listed in Table 1 were computed for samples of 1500 MC events with fixed energies.

In Fig. 1 are shown two simulated muon emission events from the lead inside an OPERA brick, assuming an initial kinetic energy of 15 MeV, and the production of a μ^+ (left) and a μ^- (right).

^aThese thicknesses have been found to be adequate with a Monte Carlo simulation considering the effects of 0.5÷2.6 MeV photons, which could produce electrons mimicking the searched events.

Table 1. Percentage of events as a function of the minimum number of emulsion films crossed by both μ (N_μ) and e (N_e), for different μ initial energies (col. 1).

N_μ N_e	2 0	2 2	2 4	2 6	4 0	4 2	4 4	4 6	6 0	6 2	6 4	6 6
5 MeV	12	10	9	7	-	-	-	-	-	-	-	-
7 MeV	25	23	21	14	-	-	-	-	-	-	-	-
10 MeV	51	46	41	31	0.6	0.5	0.4	0.3	-	-	-	-
15 MeV	74	66	58	44	31	28	23	17	1	1	0.9	0.7
20 MeV	84	72	63	49	56	50	40	30	29	26	21	15
25 MeV	89	75	66	50	70	60	49	36	48	42	34	25
30 MeV	92	75	67	52	78	66	54	36	60	51	42	28

4. Estimates of global detection efficiencies

The geometrical ϵ_g have to be multiplied by the μ^\pm and e^\pm reconstruction efficiencies to obtain the total efficiency. With the OPERA tracking procedure,¹⁰ the mean detection efficiency for each “microtrack” in one emulsion film is $\simeq 95\%$. The instrumental limit of 0.8 rad on the incident direction introduces an event selection of $\sim 30\%$. The “base track” (obtained from 2 microtracks separated by the plastic base) reconstruction efficiency is $\simeq 90\%$ ($95\% \times 95\%$). The top-bottom linking efficiency, mainly due to the multiple scattering in the plastic base, ranges from the $\sim 50\%$ for 5 MeV particles to $\sim 99\%$ for particles with energies ≥ 20 MeV. The base track linking efficiency is $\sim 6\%$ for the whole range of initial muon energies.

The detection efficiency ϵ_{tot} for a muon crossing at least n emulsion films is the product of the percentage of events with these topological requirements ϵ_g (col. 6 of Table 1), the 30% given by the angular limit, n times the 95% efficiency for the microtracks, $n/2$ the top-bottom linking efficiency and the linking efficiency between the base tracks. Table 2 shows the % efficiencies ϵ_g and ϵ_{tot} computed requiring at least 2 emulsion films crossed by the muon (col. 2-3) and 4 emulsion films crossed by the muon (col. 4-5). The values refer to the present OPERA tracking.¹⁰

As the expected halflives $t_{1/2}$ are much larger than any reasonable exposure time T , the expected sensitivities are estimated from

$$\frac{\delta N}{N_0} = \frac{\ln 2}{t_{1/2}} T \epsilon_{tot} \quad (3)$$

where $\delta N = 2.3$ is the number of events corresponding to a 90% C.L. limit assuming no candidates, N_0 is the initial number of nuclei, and ϵ_{tot} is the experimental efficiency. Using one OPERA brick for one year exposure and a global detection efficiency of $\sim 10\%$, a sensitivity of $\sim 7 \cdot 10^{23}$ yr (90% C.L.) could be reached.

Table 2. Geometric efficiencies (ϵ_g) and total muon detection efficiencies (ϵ_{tot}) as a function of the initial muon energy computed on the basis of the OPERA tracking procedure for $N_\mu = 2$ (col. 2-3) and for $N_\mu = 4$ (col. 4-5). All values are in %.

E_μ	$N_\mu = 2$		$N_\mu = 4$	
	ϵ_g	ϵ_{tot}	ϵ_g	ϵ_{tot}
5 MeV	12	1.5	-	-
7 MeV	25	4.3	-	-
10 MeV	51	12	0.6	0.006
15 MeV	74	19	31	0.4
20 MeV	84	22	56	0.8
25 MeV	89	24	70	1
30 MeV	92	25	78	1.1

5. Conclusions and perspectives

A test search for spontaneous emission of muons from Pb nuclei, using some OPERA lead/emulsion bricks, was described. We are in the process of making a complete simulation of the detector including its response and the track reconstruction efficiencies. We have shown that stringent limits for spontaneous muon radioactivity may be reached: $t_{1/2} \geq 7 \cdot 10^{23}$ years.

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